Lubricant Thickness Modulation Induced by Head-Disk Dynamic Interactions

Xiaoding Ma, Huan Tang, Michael Stirniman, and Jing Gui

Abstract—The behavior of a thin lubricant film under a flying head has been studied by examining the lubricant redistribution on the disk after flying, using an HDI-SRA instrument. Lubricant depletion tracks were observed on the disk surfaces and, more interestingly, the lubricant film was found to exhibit a periodic thickness modulation in the downtrack direction. The wavelength of the lubricant thickness modulation is found to increase linearly with the disk linear velocity, and depends weakly on the lube type and lube bonding ratio. The amplitude of the modulation grows slowly with flying time. Both negative-pressure air bearing pico sliders and catamaran-style positive-pressure nano sliders generate similar patterns on lubricant films. The frequency of the thickness modulation is in the range of 40–50 kHz, and is attributed to interactions of the disk lubricant with the slider roll mode. In addition, for highly-bonded lubricant films, a much finer lubricant modulation pattern can be seen with a frequency of 196 kHz, which is very close to the frequency of the pitch mode of the slider. These results indicate that the lubricant thickness modulations on the disk are generated by slider-disk dynamic interactions, and are due to slider body motions.

Index Terms—**Flyability, head-disk interaction, lubricant, slider air bearing, waviness.**

I. INTRODUCTION

IN A magnetic hard disk drive, an ultrathin layer (~1–2 nanometers) of perfluoropolyalkylether (PFPE) is applied to the media surface, typically overcoated with 5 nm of amorphous carbon, to improve the tribological properties. The wear durability of the media depends strongly on the retention and replenishment of the lubricant on the protective overcoat surface. A lot of work has been done to gain a fundamental understanding of the surface mobility of topical lubricant for its importance in providing a path to more robust head-disk interface designs [1]–[5]. However, little effort has been made in the past to study the lubricant's behavior under a flying head, because of the fact that the lubricant layer was very thin as compared to the fly height of the head and the disk carbon overcoat thickness. With the growth of magnetic recording areal density, the head-medium separation (HMS) continues to decrease. The fly height of the head has now been reduced to such an extent that the effect of the lubricant layer is becoming more and more evident. We have studied the effect of the lubricant layer on magnetic recording performance [6] and demonstrated that the liquid lubricant layer contributes to the HMS in the same manner as a solid overcoat such as carbon film. In other words, the liquid lubricant film adds at least its full thickness into the magnetic spacing, regardless whether it is bonded or free. Not only does the nominal lubricant film thickness matter, as reported by Toney, Mate and Leach [7], [8], on an ultrasmooth media the "roughness" of the lubricant film due to thermal agitation, i.e., capillary wave, also contributes to the magnetic spacing. Naturally, one may speculate that the dynamic interactions between the lubricant film and the slider may also influence the recording performance. Indeed, we observed significant slider vibration induced by the presence of a thick lubricant film (≥ 3 nm) when the slider flies close to the disk surface ($<0.5\ \mu''$), whereas such vibrations were completely absent in the regime of thin lubricant films (~1 nm) [9]. Kohira *et al.* also reported a strong dependence of the disk glide avalanche behavior on the lubricant film thickness such that the disk with a thicker lubricant film appeared to have a higher glide avalanche point [10]. We also found that lubricant can be "carried" by a flying slider from the thick lubricant region and deposited in the thin lubricant region. Two possible mechanisms were identified to explain this slider-assisted lubricant transfer phenomenon, which are slider-enhanced evaporation-condensation and high pressure "pushing" by the air bearing [9]. The effect of nonuniform lubricant film distribution and lubricant dewetting on head-disk dynamics has also been investigated [11]. While lubricant dewetting did impact the stability of a flying head, self-repairing has been observed which over time reduced the head vibration. All of those studies have shown that, as the recording head flies closer and closer to the disk surface, the effect of the lubricant layer on head-disk dynamics becomes increasingly more pronounced.

Clearly, in many respects, the behavior of a liquid lubricant film closely resembles that of disk surface topography. Disk surface topography can be conveniently divided into three wavelength regimes, roughness, flatness and waviness corresponding to topographical features much smaller than, much greater than, and comparable to that of a slider, respectively [12], [13]. Depending on the slider response, these features of different wavelength influence recording performance in different ways. The roughness and flatness can cause static spacing loss, but waviness (or microwaviness) can couple to the slider air bearing modes, leading to HMS modulation. As mentioned above, the effects of lubricant film in both the roughness regime (capillary wave) and the flatness regime (large-scale thickness nonuniformity) have been studied. It remains unclear, however, whether or not any lubricant effect exists in the waviness regime. To answer this question, one has to first identify such features, if any, in a lubricant film that have the characteristic length comparable to that of a slider. Recently, Pit *et al.* [14] have reported the formation of lubricant thickness nonuniformity or "Moguls" un-

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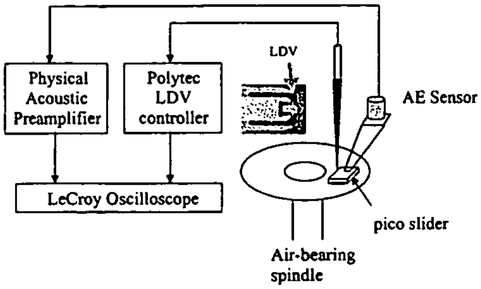

Fig. 1. Experimental setup of flyability test.

derneath a flying slider. They found that the lubricant moguls are strongly correlated to the underlying substrate topography but have no periodicity. In this work, the lubricant film topography under a flying head has been studied using an HDI-SRA instrument in an attempt to answer the question whether a waviness-like feature exist in a lubricant film, and if it does, what the main characteristics of these features are.

II. EXPERIMENT

The samples used in this work were 95 mm aluminum disks with magnetic layer and 5 nm carbon overcoat. The average surface roughness is about 0.5 nm, as measured by atomic force microscopy (AFM). Two types of PFPE lubricants were used in this work: Zdol and Ztetraol, which are difunctional perfluoropolyether polymers with similar mainchain structure but different end-groups:

$$X-CF_2-[(OCF_2-CF_2)_n-(OCF_2)_m]-OCF_2-X$$

where $n/m \cong 1$, and $X = CH_2OH$ for Zdol, and $X = CH_2OCH_2CH(OH)CH_2OH$ for Ztetraol. There are two molecular weights for Zdol: high molecular weight (HMW) $Mn = 4000$ g/mol, and low molecular weight (LMW) $Mn = 1900$ g/mol. The molecular weight of Ztetraol is 2500 g/mol. The nominal lubricant film thickness is 2 nm with bonding ratio either at 50% by conventional dip coating process or at 95% achieved by vapor phase deposition.

A schematic of the experimental setup, which mainly consists of an air bearing spindle, a head mount fixture, an LDV unit, and an acoustic emission (AE) sensor, is shown in Fig. 1. The laser spot of the LDV unit was focused on the rear end of the head to monitor the head motion. The AE sensor was mounted on the arm supporting the head for detection of head-disk contact. Both the LDV and AE signals were recorded with a 1 GHz LeCroy digital oscilloscope. Two types of sliders, a pico slider with a negative-pressure air bearing and a nano slider with a catamaran-style positive-pressure air bearing, were used in the work. During the experiment, the head was dynamically loaded and flew on a fixed track at zero skew for a specified period of time before being dynamically unloaded.

The disks before and after being flown over were examined with Scanning Reflectance Analysis (SRA) made by HDI Instrumentation. The phase contrast reflectivity channel, with a sensitivity of better than 0.1 Å, was used to detect lubricant film thickness variations on the surface. The measured reflectivity was converted into lubricant film thickness in nanometers using a predetermined calibration factor between the HDI-SRA and an FT-IR instrument. The lateral resolution of HDI-SRA is around 2 μm, which is obviously inadequate to resolve "roughness" features but should be sufficient to resolve waviness features, the characteristic length of which ranges from 100 μm to a few millimeters.

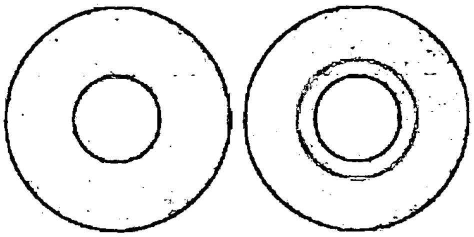

Fig. 2. Lubricant film images by HDI-SRA. Left: before test. Right: after test.

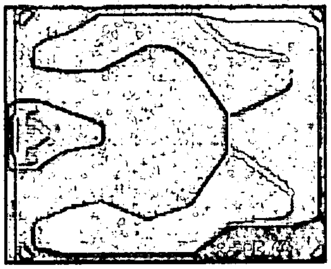

Fig. 3. The picture of a negative-pressure air bearing pico slider used in this work.

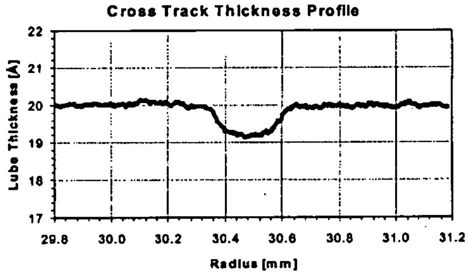

Fig. 4. Crosstrack lubricant film thickness profile for the disk in Fig. 2.

III. EXPERIMENTAL RESULTS

A. Lubricant Redistribution

Fig. 2 shows the HDI images of lubricant Zdol over the disk before and after 10 min of flying test using a negative-pressure ABS pico slider with a fly height of 0.5 μ'' shown in Fig. 3. During the flying test, there is no indication of head-disk contacts from AE and LDV signals. From Fig. 2, one can see that there is a lubricant depletion track after test. The crosstrack lubricant thickness profile is shown in Fig. 4. The width of the depletion track is about the same as that of the slider central rail. After 10-min flying, the lubricant film thickness inside the track decreases by slightly less than 1 Å. Interestingly, no lubricant buildup is seen outside of the slightly depleted track. The net lubricant loss after flying is presumably caused by slider-assisted evaporation [9].

$v \approx \lambda f$
$(42 kHz)(0.07 mm)$

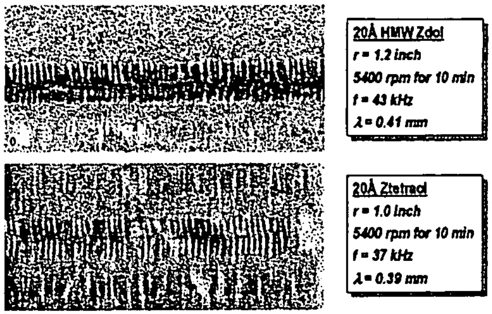

Fig. 5. Zoomed lubricant film images for HMW Zdol and Zteraol.

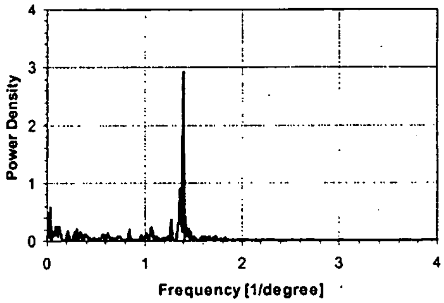

Fig. 6. FFT of lubricant thickness modulation: Zdol.

B. Lubricant Film Thickness Modulations

To search for waviness-like features, disks were further examined in the flying area by reducing the scan size during HDI-SRA measurements. Before the flying test, the lubricant film thickness appears very uniform. More specifically, no waviness-like features were observed. After the flying test, however, some waviness-like features evidently start to develop within the lubricant depletion track. Fig. 5 shows zoomed-in lubricant film images for Zdol and Ztetraol, where we can clearly see a thickness modulation pattern within the flying track. The modulation pattern is found to be highly periodic and has a single frequency mode. An example is shown in Fig. 6 for Zdol, where a single sharp peak is seen in the FFT plot. The wavelength and frequency of the modulation are 0.41 mm and 43 kHz, respectively for Zdol; and 0.39 mm and 39 kHz, respectively for Ztetraol. It should be noted that despite the apparent sharp contrast seen in the HDI-SRA images, the modulation amplitude is relatively small, usually no more than 2 Å peak-to-peak.

It should be emphasized that these waviness-like features were observed only within the flying tracks. They did not exist outside of the track. In other words, disk spinning alone does not generate these features. The modulation is induced by the flying head.

C. Effect of Linear Velocity

The same test was repeated at different RPMs and at different radii on disks with Zdol lubricant of different molecular weights, as well as different bonding ratios. Fig. 7 shows the wavelength and frequency of the lubricant film thickness modulation as a function of disk linear velocity for different lubricants at different radii and different disk rotation speeds. From these results, we can make the following observations: First, the lube modulation wavelength increases linearly with increasing disk linear velocity. Under a constant disk linear velocity, the wavelength of the modulation remains constant regardless of the radius and disk rotating speed. Second, for the same lubricant (e.g., Zdol), the film at higher bonding ratio (e.g., coated via a vapor deposition process) has a slightly longer modulation wavelength than the film at lower bonding ratio (e.g., coated via a dip process). Third, the modulation wavelength shows little dependence on the MW of a lubricant, but has a weak dependence on the end-group of the lubricant. Ztetraol, for example, exhibits a slightly longer modulation wavelength than Zdol. Finally, the modulation frequencies all fall within a narrow range between 40 and 50 kHz, and are relatively insensitive to the linear velocity.

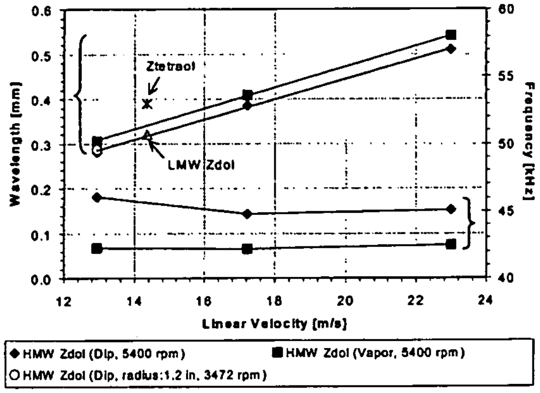

Fig. 7. Lubricant modulation wavelength and frequency as a function of linear velocity.

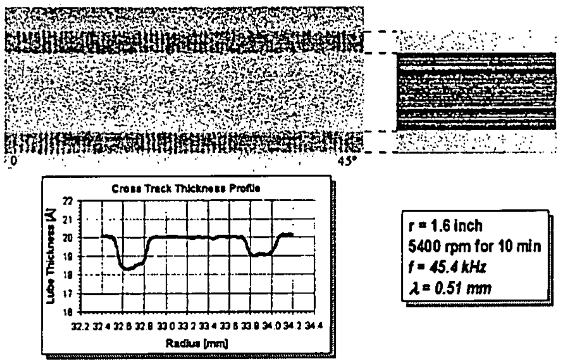

Fig. 8. Lubricant film image, slider image, and the crosstrack thickness profile for Zdol coated disk after test.

D. Slider Effect

The effect of slider geometry and air bearing design on the modulation behavior of lubricant film is evaluated by performing the same flying test on a vapor-lubed (Zdol) disk using a nano slider that has a catamaran-style positive-pressure air bearing and flies at around 1 μ'' flying height. The image of the lubricant film after test, as well as the picture of the slider, are shown in Fig. 8. Also plotted in the same figure is the crosstrack lubricant thickness profile from the region shown above. As opposed to primarily a single lube depletion track generated

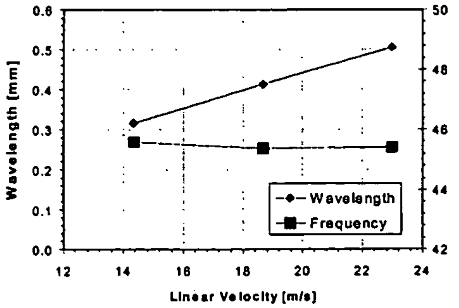

Fig. 9. Lubricant film thickness modulation wavelength versus linear velocity.

by the center-rail of the negative-pressure slider, there are two lubricant depletion tracks, corresponding respectively to the inner and outer rails of the two-rail catamaran slider. From the image of the lubricant film, one can see the waviness-like thickness modulation inside each track. The wavelength and frequency of these modulations are the same for both tracks, and they are 0.51 mm and 45.4 kHz, respectively.

Fig. 9 shows the wavelength and frequency of the modulation as a function of linear velocity. Similar to the findings from the negative-pressure sliders, the wavelength is found to be dependent on the disk linear velocity. The higher the disk linear velocity, the longer the film thickness modulation wavelength. The frequency is nearly a constant around 45 kHz. This result indicates that such slider-induced lubricant film thickness modulation is not unique to the pico slider, nor is it specific to the native-pressure air bearing. Given the fact that very similar modulation patterns were observed with two vastly different sliders, it is indeed quite reasonable to speculate that this phenomenon can occur under all types of sliders.

E. Flying Time Effect

The lubricant modulation as a function of the flying duration was also investigated. A catamaran-style nano slider was used to fly over a Zdol-coated disk (by dip-coating) for different duration from 1 min to 1 h. Fig. 10 shows the images of the lubricant film after flying for (a) 1 min, (b) 5 min, (c) 10 min, and (d) 60 min. Apparently, even for a short period of 1 min, a distinct periodic modulation feature has already developed. As the flying duration increases, the film thickness modulation becomes more pronounced, whereas the modulation frequency remains constant. The amplitude of the modulation increases steadily with the flying duration as shown in Fig. 11, which clearly suggests a phase relationship between successive excitations, or a resonance phenomenon.

Fig. 10(e)–(h) show the lubricant images taken on the same tracks one day after the fly test. The modulations are still visible but much less pronounced. This is because the surface diffusion of lubricant molecules, driven by the disjoining pressure gradient, tends to smoothen out the thickness nonuniformity. The modulation amplitude reduction is directly proportional to the original modulation amplitude, as shown in Fig. 12, which is entirely consistent with surface diffusion acting as the recovery mechanism and thickness gradient acting as the driving force for the recovery [2].

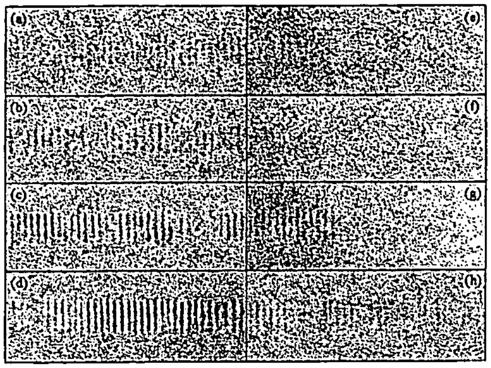

Fig. 10. Images of lubricant film under one rail of the catamaran slider after flying for (a) 1 min, (b) 5 min, (c) 10 min, and (d) 60 min. Images (e)–(h) are taken on the same tracks 1-day after the tests.

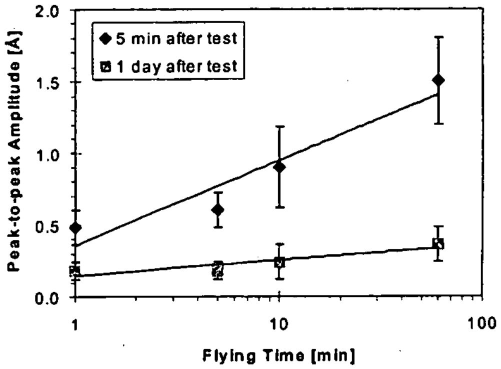

Fig. 11. Amplitude of lubricant film thickness modulation, measured at 5 min or 1 day after the test, as a function of flying time.

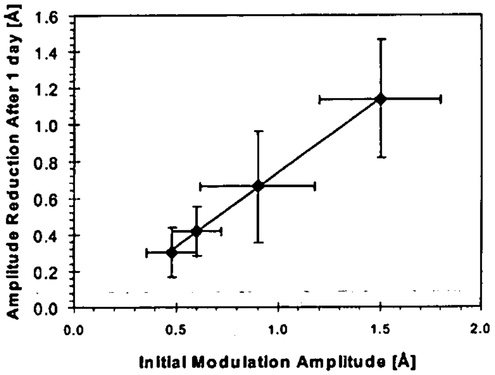

Fig. 12. The reduction of the amplitude of lubricant film thickness modulation versus the initial modulation amplitude.

IV. DISCUSSION

At the head-disk interface, the slider is flying at very close proximity to the lube layer. There are a number of forces acting on the lubricant layer due to the presence of a flying slider, which include slider generated air pressure gradients and slider generated air shear [15]. To move the lubricant molecules, these forces have to overcome the molecular forces, such as disjoining

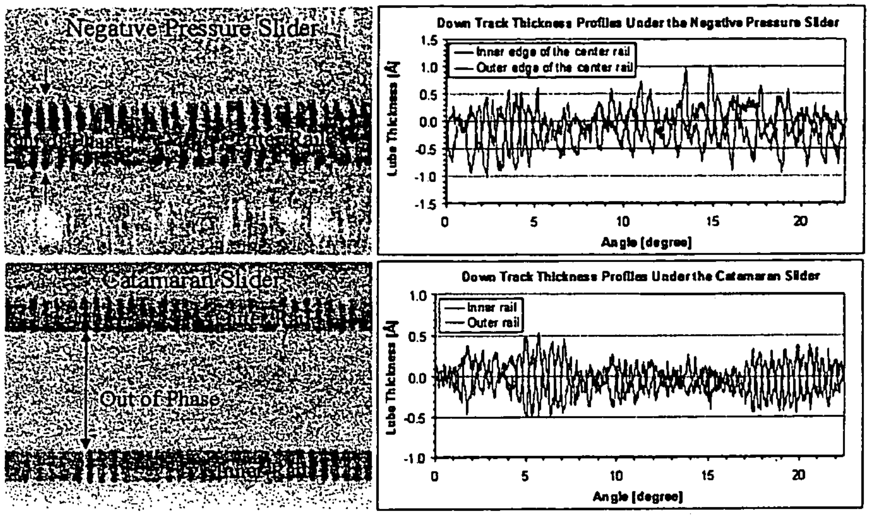

Fig. 13. Lubricant images after test and the corresponding thickness profiles.

pressure which can be expressed as follows (assuming purely van der Waals interactions):

$$\Pi = \frac{A_H}{6\pi h^3} \tag{1}$$

where A_H is the Hamaker constant, and h is the film thickness. For a 20 Å lube film, the force is about 10^{-12} N/molecule. The slider generated air pressure gradients exerts a force on the lubricant layer to push the lubricant molecules out from underneath the slider body. The slider generated air shear force will push the molecules in the direction of the slider motion. Coupled with the resonance of the slider air bearing, these forces associated with the flying slider may be able to generate the observed lubricant thickness modulation patterns.

There are three primary air-bearing modes, which are the trailing-edge pitch mode, leading edge pitch mode, and roll mode. Their frequencies typically range from ~40 kHz for the roll mode to ~200 kHz for the trailing-edge pitch mode. As the fly height increases, the air-bearing frequencies decrease. The frequency of lubricant film thickness modulation coincides very well with the slider roll mode, leading to a conjecture that the modulation is caused by slider roll motions. In fact, upon a further examination of the lubricant film images, we found that the thickness modulation patterns are consistent with this hypothesis. As shown in Fig. 13(a), for a negative-pressure slider, the thick lube regions corresponding to the inner-edge of the center-rail align precisely with the thin lube regions corresponding to the outer-edge of the center-rail. The same pattern arrangement can also be observed on the catamaran-style slider, where the modulations corresponding to the inner-rail and those corresponding to the outer-rail are exactly 180° out of phase, as shown in Fig. 13(b). This behavior can be more clearly illustrated by the downtrack lube profiles, shown in Figs. 13(c)–(d). For the negative-pressure slider and under the center rail, the lube thickness peaks (valleys) on the inner-edge are aligned exactly with the lube thickness valleys (peaks) on the outer-edge. Similarly, for the catamaran-style slider with two rails, the lube thickness peaks (valleys) in the track corresponding to the inner-rail are exactly aligned with the lube thickness valleys (peaks) in the outer-rail. This observation provides the strongest evidence that the modulation is induced by the slider roll motions. When a slider rocks along its central line, its motion is different in phase by exactly 180° from one side to the other.

The results shown in Figs. 10 and 11 clearly indicate that the ripples generated on the lubricant film are not made and wiped out with every turn. Rather, they grow slowly with time in a fashion similar to a resonance phenomenon. It begs question, however, how this "resonance" gets initiated in the first place since no inherent feature in the lubricant film bears the frequency of the slider roll mode. As we know, the slider roll mode has a certain frequency spread. When a slider repeatedly flies over a disk along a fixed track, the slider roll motion may be locked on to a specific frequency within this mode which is commensurate with the disk rotation frequency, hence the occurrence of phase locking (analogous to the frequency locking of a lasing cavity). The locked frequency may depend on the properties of the slider and the disk. The high air-bearing pressure at the trailing edge deforms, or depresses, the lube film locally. The coupling of the localized deformation of the lube film with the phase-locked slider body motion gradually leads to the buildup of lube film thickness modulation after repeated flyover.

It would be interesting to see if lubricant modulation patterns corresponding to other primary air bearing modes can also be observed. Fig. 14 shows the lubricant film images after the flying test on a vapor-lubed disk. Besides the very visible modulation patterns at 42 kHz due to the roll mode, an even finer pattern, albeit less pronounced, can indeed be identified inside the track. This pattern has a wavelength of 88 μm and a frequency of 196 kHz, which closely matches the frequency of the trailing-edge pitch mode of the slider. Since the frequency of the pitch mode is significantly higher than the roll mode, it is expected that the modulation amplitude is smaller, making it harder to observe. More importantly, because lubricant

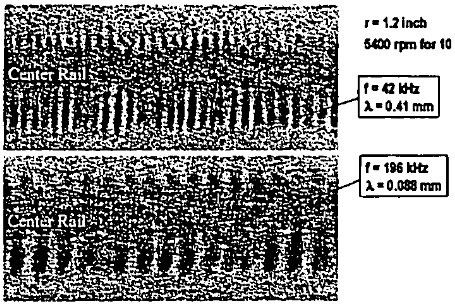

Fig. 14. Images of the lubricant film on a vapor-lubed (Zdol) disk after test.

molecules are mobile, they could readily "self-repair" to erase such small undulations over a small distance. In fact, we were able to observe this high frequency mode on a vapor-lubed disk because the high bonding ratio associated with the vapor-lubing process limited the surface mobility of lubricants. The observation of this mode further indicates that the lubricant thickness modulation is a result of the dynamic interactions between the lubricant film and the slider body motions.

It is known that the disk surface topography with wavelengths comparable to the slider length, also known as microwaviness, could be particularly detrimental to the recording performance and reliability of a high areal density disk drive [12]. Because the wavelength of such topographical features falls within the range of air bearing modes, hence, they are prone to induce slider motions, thus leading to significant HMS modulation. Within a lubricant film there are no inherent waviness-like features. However, under a flying head, the slider motions can induce such waviness-like features within the lubricant film. As the head continues to fly on-track, the amplitude of the waviness in the film grows, which in turn can cause the amplitude of the slider motion to increase. Nevertheless, such dynamic coupling between the slider motion and lubricant film thickness modulation is not likely to grow forever because lubricant molecules are mobile. The modulation amplitude may only grow to such an extent that the disjoining pressure gradient balances out the driving forces for lubricant film modulation. The amplitude of such steady-state modulation depends strongly on the lubricant types as well as the chemical nature of the carbon overcoat, which is an interesting subject of further investigation.

V. SUMMARY

Lubricant thickness modulation underneath a flying head has been observed for both negative-pressure pico sliders and catamaran-style positive-pressure nano sliders. The wavelength of these waviness-like features is proportional to the linear velocity of the disk, and depends to a lesser extent to lubricant type or lubricant bonding ratio. The frequency of the modulations is relatively insensitive to the linear velocity, nor does it change with flying time. It is always in the range of 40–50 kHz corresponding to the roll mode of the slider. The amplitude of the modulation, on the other hand, increases steadily with flying time, suggesting a phase-locking resonance phenomenon. For lubricant film with high bonding ratio, besides the modulation pattern with the frequency at 46 kHz, a much finer lube pattern can be seen with the frequency at 196 kHz. This frequency is very close to that of the pitch mode of the slider. The result indicates that the lube thickness modulation is generated by slider-disk dynamic interactions, and is due to the slider body motions.

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